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13. ABSTRACT *(Maximum 200 words)*

Optical techniques for spectral domain processing (SDP) by frequency mixing of laser beams in optical waveguides have been investigated. A theoretical model for calculating nonlinear coefficients and dispersion characteristics of asymmetric quantum wells has been developed and applied in a novel design for a frequency conversion device. A new quasi-phase-matching approach to obtaining high conversion efficiency in optical wave-guides has been proposed and analyzed. The quantitative analysis predicts conversion lengths as short as 112 microns with a power density of 1 MW/cm^2 at the optical pump wavelength of 1.3 microns. A dense wavelength-division-multiplexed (WDM) network which makes use of thefrequency conversion device to obtain rapid switching between channels has been designed. Nonlinear devices in each node convert an incoming carrier to any frequency in an entire wavelength regime in a few nanoseconds, ensuring a low latency time in the network.

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SPECTRAL DOMAIN OPTICAL PROCESSING TECHNIQUES

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SPECTRAL-DOMAIN OPTICAL PROCESSING TECHNIQUES

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SPECTRAL-DOMAIN OPTICAL PROCESSING TECHNIQUES

1. Summary

The objective of this research was to investigate the design, fabrication, and network application of frequency mixing devices in nonlinear optical waveguide materials. In particular, multiquantum well (MQW) semiconductor materials may provide orders-of-magnitude improvement in nonlinear conversion efficiency over conventional bulk nonlinear materials. Optical wavelengths of interest are those in the near-infrared spectral regimes commonly used for optical fiber communication. For example, an optical carrier at a wavelength of 1.3 μm can be mixed with mid-infrared light at 8.06 μm to produce a frequency-shifted carrier at 1.55 μm. It may be possible to design practical networks with as many as 5000 nodes which can support multigigabit-per-second channel data rates with reconfiguration times as short as a few nanoseconds.

In the design area, we have perfected a theoretical model for calculating nonlinear coefficients and dispersion characteristics of asymmetric quantum wells, and have applied it in a novel design for a frequency conversion device. We believe the model to be unique in that it considers bound-continuum as well as bound-bound transitions. We have proposed and analyzed a new quasi-phase-matching approach to obtaining high conversion efficiency in optical waveguides. The approach would make use of Zn diffusion in AlGaAs MQW material. The diffusion is known to cause a homogenization of the heterostructure layers, thus quenching the nonlinear interaction. By diffusing the Zn through a spatially periodic mask, quasi-phase-matching can be achieved over a long interaction distance. The quantitative analysis predicts conversion lengths as short as 112 μm with a power density of 1 MW/cm^2 at the optical pump wavelength of 1.3 μm. In this case the quantum wells contained a step asymmetry in the potential. The wells had two bound states with the bound-to-bound transition near the mid-infrared photon energy corresponding to a wavelength of 8.06 μm. Even larger nonlinearities may be possible in structures which utilize two resonances of an asymmetric quantum well with three bound states.

We have designed a dense wavelength division multiplexed network which makes use of the frequency conversion device described above to obtain rapid switching between channels. The system is intended to make efficient use of the 50 GHz of bandwidth available in a single fiber in the 1.3 and 1.55 μm regimes. The destination of a data packet is determined by the carrier frequency injected into the network at the source terminal. Nonlinear devices in each node make it possible to convert an incoming carrier to any frequency in an entire wavelength regime in a few nanoseconds. This rapid tunablity, together with the fact that no processing of the packets is needed at the nodes, provides for low latency time in the network. Further latency reduction as well as improvement in the optical power budget are achieved by multidimensional connectivity. Schemes to recover from packet collisions have also been devised.

2. Background

A nonlinear interaction between two or more information carriers is required to perform most useful logic and computational functions. The use of optical carriers for high-speed digital processing is attractive from the standpoint of high carrier frequency, low propagation delay, and

the potential for parallel processing. Most optical logic schemes which have been proposed have made use of interactions in which there is a nonlinear relation between the intensities of two optical inputs. However, due to materials limitations and the lack of architectures which can take advantage of the inherent bandwidth of the optical carriers, such schemes have not proven competitive with conventional all electronic computing methods.

Dr. Alan Craig of AFOSR has proposed a new approach to optical processing based upon nonlinear interactions between optical carriers in the frequency domain. A computing device using this approach can be termed a "spectral domain processor" (SDP). One approach to the SDP would utilize difference frequency mixing (DFM) and/or sum-frequency mixing (SFM) as the fundamental interactions; i. e., two carriers at frequencies f_1 and f_2 would mix to produce an output at a frequency $f_3 = f_1 \pm f_2$.

Key considerations in the design of an SDP include the selection of suitable light sources and nonlinear materials, the design of logic and computing elements, and system architectures. The first of these issues, light source selection, is reasonably straightforward. Two semiconductor alloy systems have recently been developed to provide efficient, reliable sources of coherent radiation at near-infrared wavelengths: the GaAlAs system (.78-.86 μm) and the InGaAsP system (1.2-1.6 μm). The active layer composition for a particular laser determines its emission wavelength within the spectral range. Furthermore, GaAlAs lasers can efficiently pump Nd:YAG solid-state lasers to provide single-frequency emission at the intermediate wavelength of 1.06 μm. Wavelengths available from DFM and SFM using various combinations of these lasers are summarized below:

		output wavelength range (μm)	
laser 1	laser 2	DFM	SFM
GaAlAs	InGaAsP	1.5-3.0	.47-.56
Nd:YAG	InGaAsP	3.1-9.1	.56-.64
GaAlAs	Nd:YAG	3.0-4.6	.45-.47
InGaAsP	InGaAsP	> 4.8	.60-.80

Thus, a wide range of wavelengths in the visible and near-infrared spectral regions is possible using DFM and SFM. Threshold currents of less than 1 mA and wall-plug efficiencies in excess of 50% have been obtained in both GaAlAs and InGaAsP laser systems. More recently, InGaAs laser diodes which operate reliably at room temperature at wavelengths near 1 μm have been reported. When InGaAs lasers are commercially available, they can be used to further extend the range of pump wavelengths for DFM and SFM.

Of course, suitable nonlinear materials are needed for SDP to be practical. The material used for mixing the three optical frequencies should have a very large nonlinear coefficient d_{ij} and should be suitable for phase-matching at the pump frequencies f_1 and f_2 and the sum or difference frequency f_3. Conventional nonlinear infrared materials such as GaAs or CdTe do not meet these criteria. However, epitaxially-grown layered semiconductors known as multiple quantum well (MQW) materials are predicted to have very large nonlinear optical coefficients [1]. Experimentally, second harmonic generation in GaAlAs MQWs using a 10.6 μm CO_2 pump laser has been reported [2,3].

The quantum wells are layers of relatively low energy gap sandwiched between barrier layers with larger energy gaps. Electrons or holes trapped in these wells occupy discrete quantum-mechanical energy eigenstates. The optical nonlinearities result from electric dipole transitions of charged carriers between the ground state and excited states of the wells, which are termed intrasubband transitions. Large, resonantly enhanced nonlinearities occur when these transition energies are near photon energies of the interacting light waves.

The symmetry of the quantum wells is a key consideration in the design of MQW devices. Energy level diagrams and wave functions for symmetric and asymmetric wells are illustrated in Fig. 1. The nonlinear coefficient d_{33} is proportional to the product of dipole matrix elements $y_{ab}y_{bc}y_{ac}$. For the symmetric well, the wave functions ua and uc are symmetric with respect to the center of the well. Since the electric dipole perturbation is proportional to y, which is antisymmetric, then $y_{ac} = 0$ for the symmetric well. In this case, the nonlinear coefficient vanishes. Thus, an asymmetric well, for which in general $y_{ac} = 0$, is needed for the nonlinear device. This is equivalent to the requirement that a nonlinear crystal have no center of inversion symmetry. Asymmetric well structures are also needed for linear electrooptic modulators in quantum well materials [4].

A configuration for DFM in MQWs is illustrated in Fig. 2. Light is coupled into a planar waveguide of the MQW material. The polarization for each of the three frequencies is oriented in the y-direction (perpendicular to the well interfaces) as dictated by the need for off-resonance excitation of dipole transitions in the wells [1-3]. The nonlinear interaction transfers energy from the pump wave at the frequency f_1 into the pump wave at lower frequency f_2 ($f_1 > f_2$) and the wave at the difference frequency f_3.

GaAlAs is by far the most commonly used material system for quantum well device studies. The epitaxial techniques for producing the layers are well developed, and the materials are transparent in the infrared to 15 μm. However, other materials might ultimately prove more effective for DFM at GaAlAs and InGaAsP laser wavelengths. The well depth for electrons in GaAlAs is limited to about 1.0 eV, with GaAs wells and AlAs barriers, which constrains the available range of resonance frequencies in the device design. Other materials systems which provide larger well depths might thus be advantageous for the DFM application. One interesting possibility is the GaAlAsP alloy system, with GaAsP wells and AlAsP barriers. The $\Gamma_1^c - \Gamma_{15}^v$ energy gap is 5.12 eV in AlP and 2.89 eV in GaP, giving an energy gap difference of 2.23 eV [5]. By contrast, the $\Gamma_1^c - \Gamma_{15}^v$ energy gap is 3.06 eV in AlAs and 1.52 eV in GaAs, so that the energy gap difference is 1.54 eV. If we assume that the well depth for electrons is proportional to the energy gap difference, then the well depth will be an decreasing function of the parameter x in the alloy system $Ga_xAl_{1-x}AsP$. Thus, it may be posslble to get well depths considerably greater than 1 eV in the GaAlAsP system. Furthermore, lattice matching should be readily obtained, since the lattce constant for AlP (5.463 Angstroms) is very close to that for GaP (5.451 Angstroms) [6]. This parallels the excellent lattice match between GaAs (5.654 Angstroms) and AlAs (5.661 Angstroms) [6].

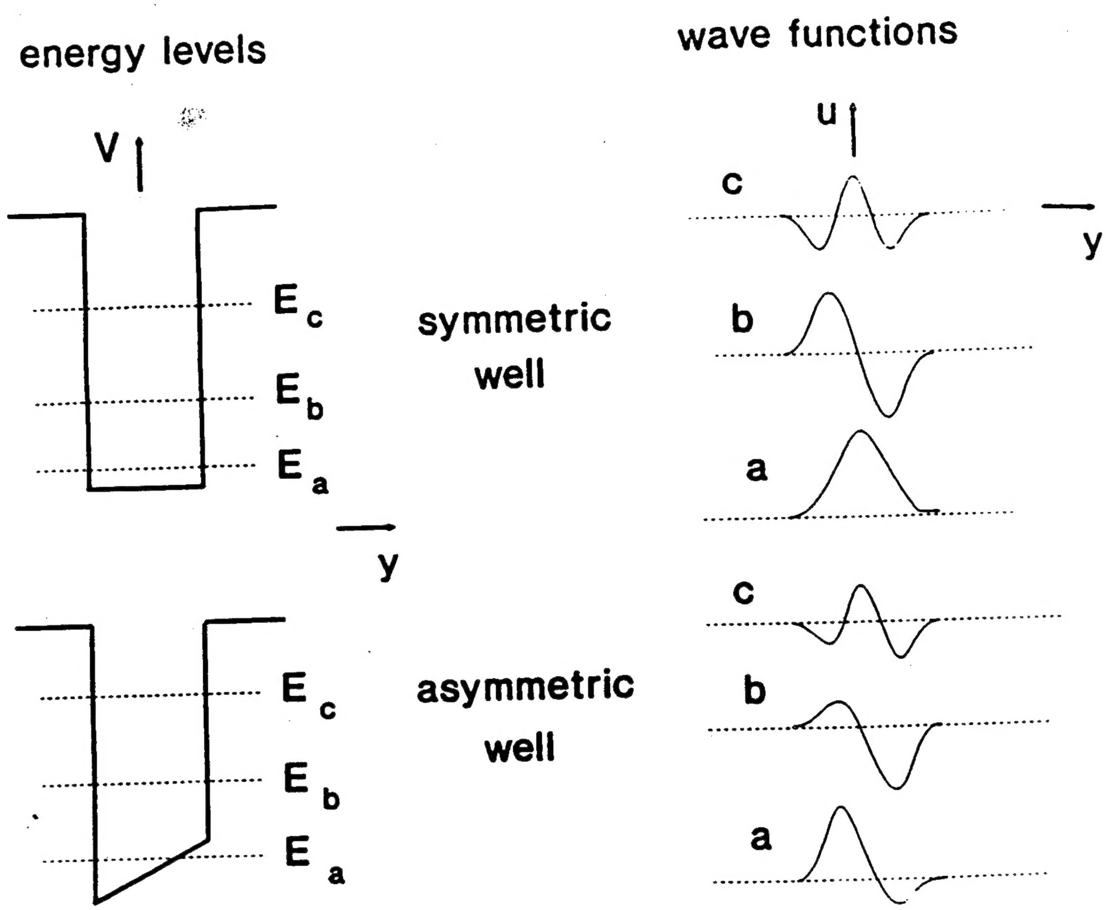

Fig. 1. A comparison of energy levels and wave functions for symmetric and asymmetric quantum wells. The matrix element $y_{ac} = 0$ for the symmetric well, so that the nonlinear coefficient vanishes. The asymmetric well, by contrast, can show large nonlinearities.

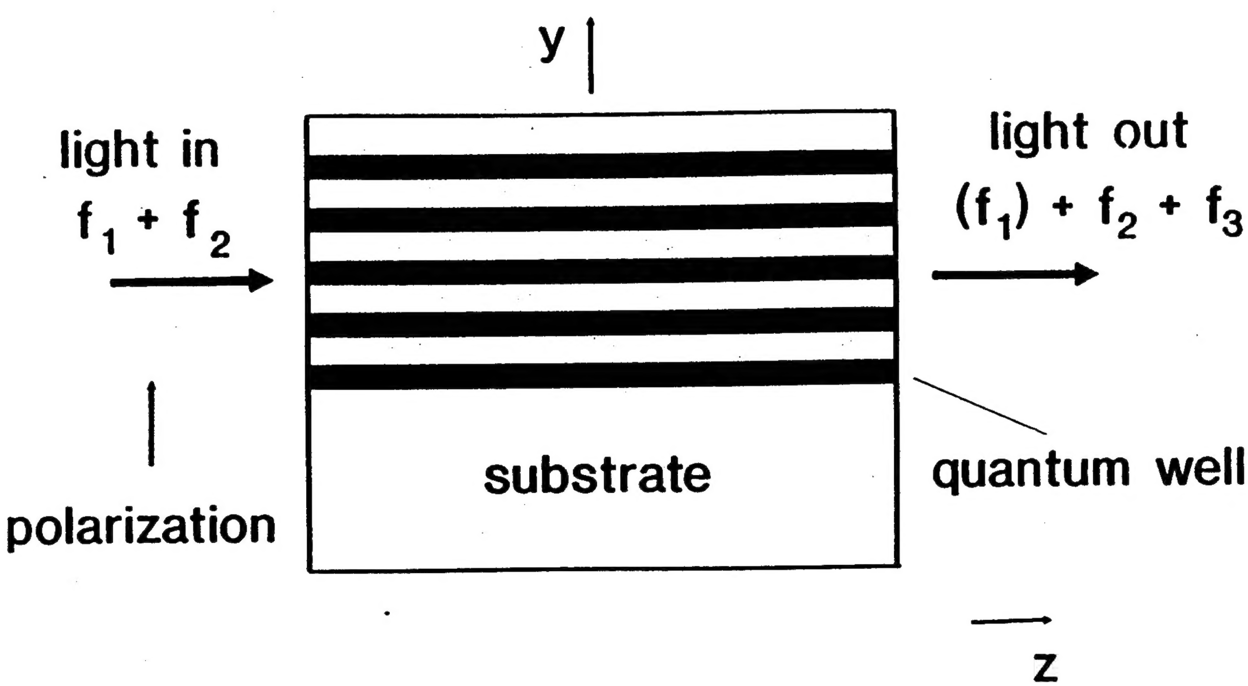

Fig. 2. A planar waveguide configuration for DFM in a MWQ material. Power is transferred from the pump at frequency f_1 to the pump at frequency f_2 and the difference-frequency wave at frequency f_3.

With the large nonlinear coefficients obtainable with MQW materials, efficient mixing can be obtained in a short distance if sufficiently high power densities are maintained at the pump laser frequencies f_1 and f_2. The best way of achieving this is to perform the nonlinear conversion in a channel waveguide of the MQW material, as in Fig. 3. The waveguide would be designed to prodvide two-dimensional confinement at all three optical frequencies, so that efficient mixing is obtained over the entire length of the device. Furthermore, the waveguides could serve as interconnections between processing elements.

Another issue is how to achieve the phase matching needed for efficient nonlinear conversion. The requirement is that the propagation vector for the optical wave at the higher pump frequency f_1 be equal to the sum of the propagation vectors for the other two frequencies. The ability to meet this requirement is determined by the dispersion characteristics of the MQW waveguide, which includes the "background" dispersion of the bulk materials, quantum well (QW) dispersion due to the dipole transitions in the wells, and waveguide dispersion. The refractive index change resulting from the quantum well transition can be quite large (of the order of unity for doping levels of $10^{18}/cm^3$ in the wells) for laser frequencies close to the dipole transition frequency (absorption line). Furthermore, the index change is positive (negative) for optical frequencies below (above) the transition frequency. However, to obtain such a large QW dispersion it is necessary to choose an operating wavelength near the peak of the absorption line, resulting in strong attenuation at that wavelength.

Two possible well designs are illustrated in Fig. 4. Here it is assumed that the laser photon energies are in the vicinity of 1.5 eV for laser 1 (a GaAlAs laser) and 0.95 for laser 2 (an InGaAsP laser). The first configuration would correspond to a relatively narrow well, with only one bound state. The transitions contributing to the nonlinearity are from the ground state to continuum states (y_{ab} and y_{ac}) and between continuum states (y_{bc}). The well parameters are chosen such that the ground-state-to-continuum absorption is bracketed in energy by the photon pump energies E_1 and E_2. The second configuration corresponds to a wider well with 3 bound states. In that case the first absorption peak is near the photon difference energy E_3 and the second absorption peak absorption is bracketed in energy by the photon pump energies E_1 and E_2.

The design of logic and computational elements for SDP has received little attention to date. However, it is clear that design rules will differ considerably form those employed in conventional electronic and optical processing schemes. Two examples with single-mode channel waveguides containing frequency mixing sections are given in Figs. 5 and 6. In the AND gate of Fig. 5, two SFM waveguide sections are used in conjunction with frequency-selective directional couplers. Two input waveguide ports and one output ports are provided: light at the frequency f_2 represents a "one", while no light at that frequency represents a "zero". The illustrations in Fig. 5 show that the truth table for the AND gate is satisfied. Furthermore, logic elements of this type can be cascaded to perform more complex digital operations. Another interesting possibility is the use of frequency mixing to perform addition and subtraction, as in Fig. 6. In this case, two DFM and one SFM waveguide sections are used. The addends are encoded as frequencies relative to f_2, as is the resultant sum. A network of Mach-Zehnder interferometers could convert the frequency-encoded optical output from the device of Fig. 6 into a parallel, binary representation of the sum.

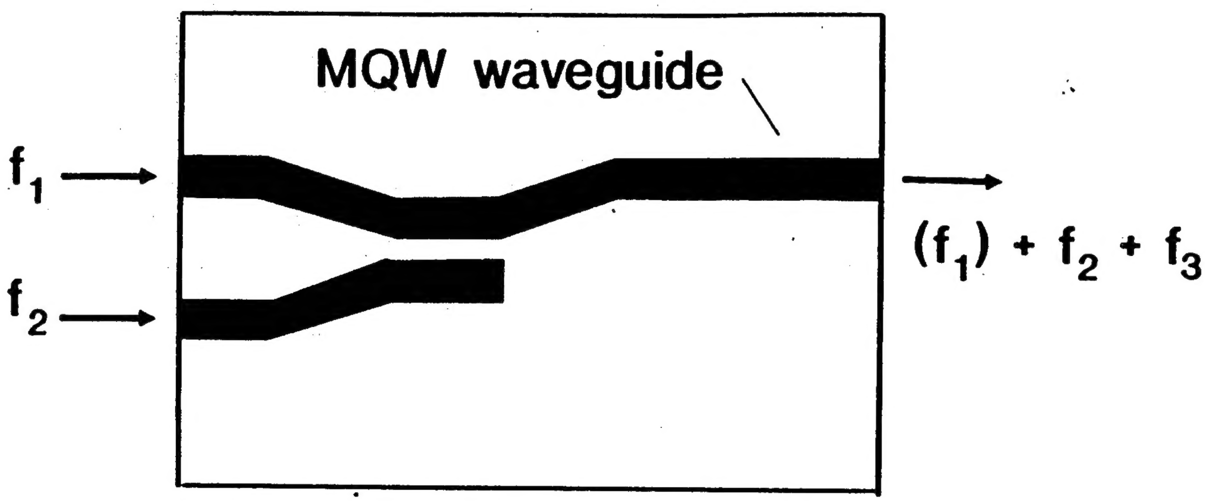

Fig. 3. Channel waveguide configuration for DFM.

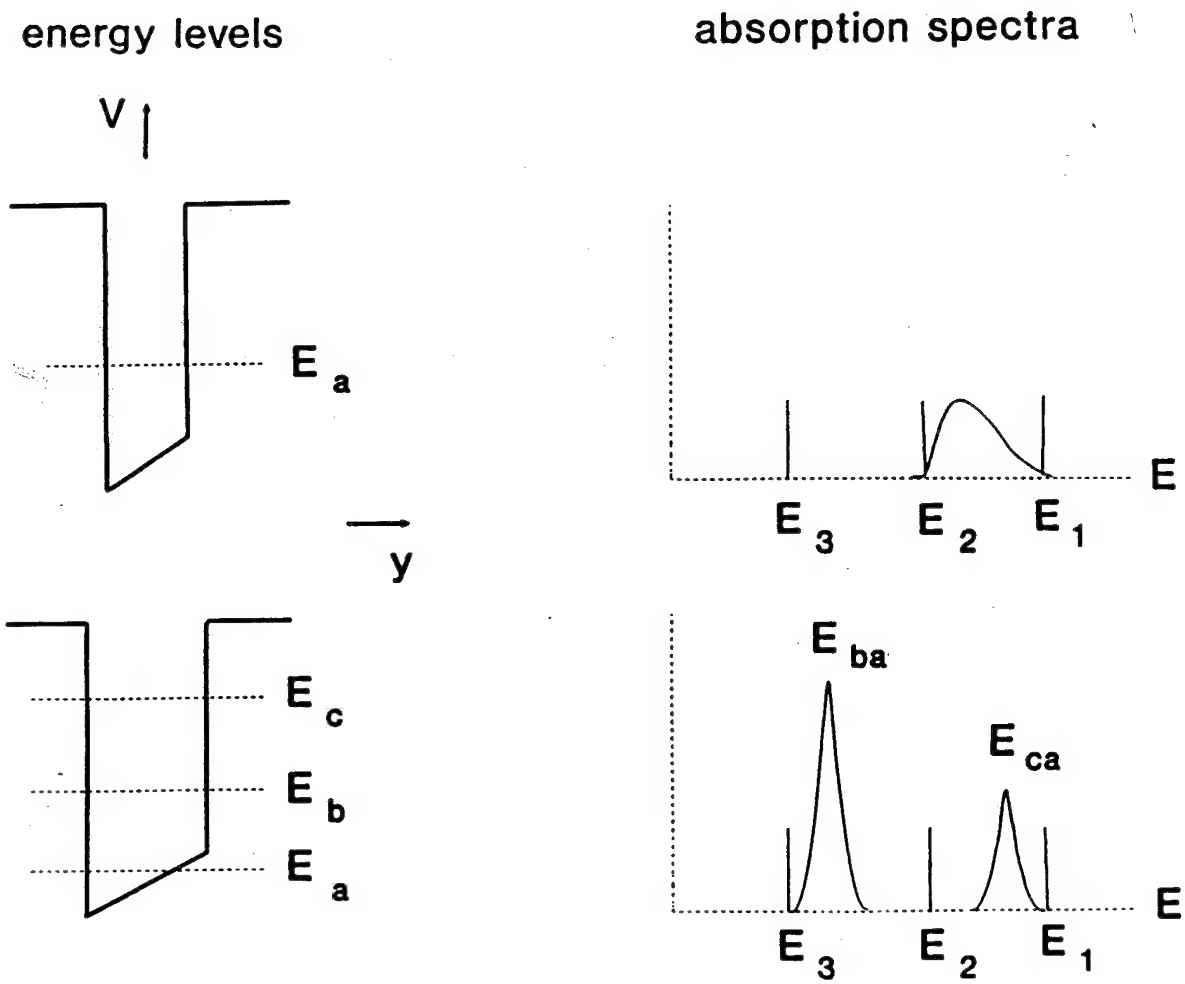

Fig. 4. Two possible well designs for DFM or SFM. The corresponding absorption spectra and laser frequencies are also shown. For the absorption spectra, it is assumed that the carriers are initially in the ground state of the well.

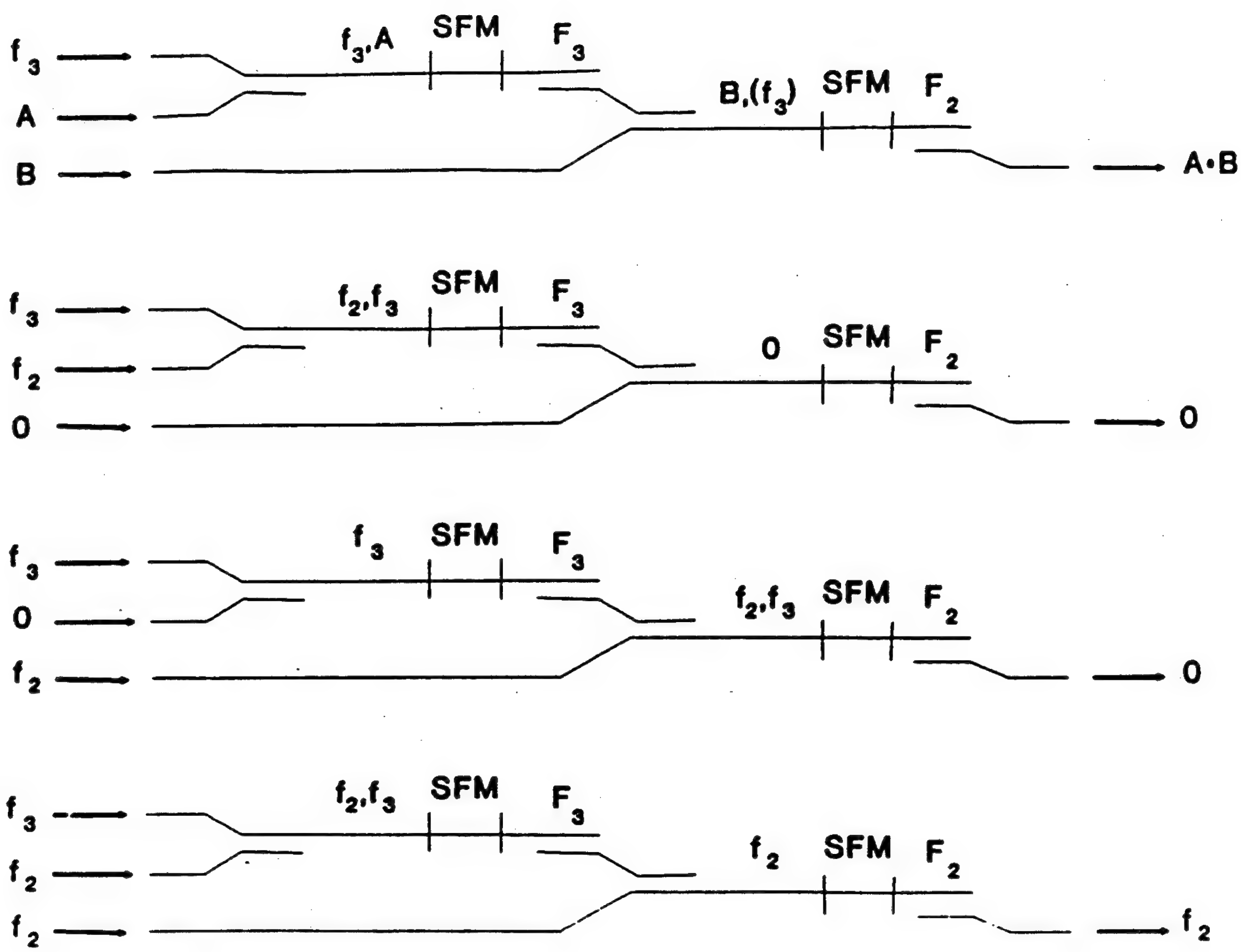

Fig. 5. AND gate using frequency mixing in channel waveguides. In the top diagram, A and B are the binary inputs and A.B is the output. The next three diagrams show the behavior for one or two "one" inputs; i. e., three of the four cases in the AND truth table.

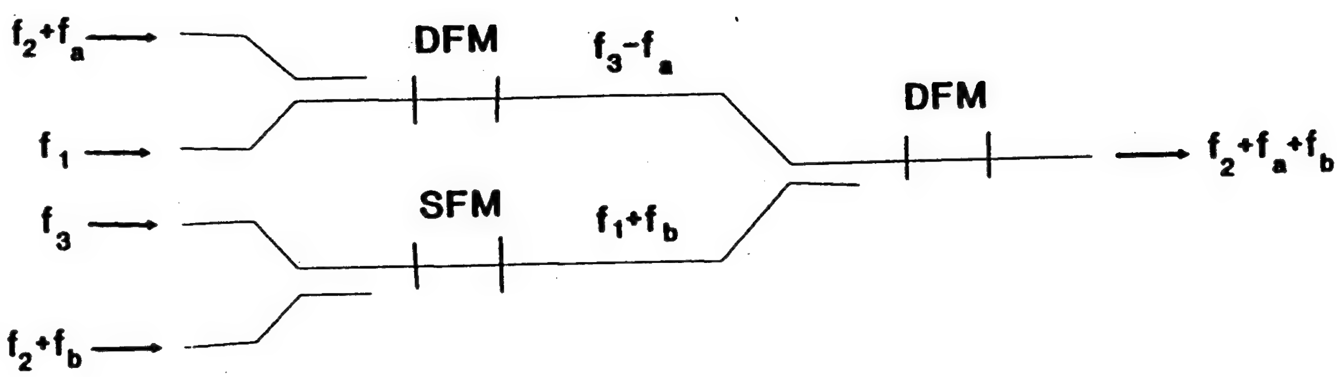

Fig. 6. SDP adder circuit.

3. Technical Objective

The objective of this research is to investigate the design, fabrication, and communication network application of frequency mixing devices in nonlinear optical waveguide materials. We are interested in designing novel frequency mixing devices in multiquantum well (MQW) semiconductor materials which can provide unprecedented nonlinear conversion efficiencies. Optical wavelengths of interest are those in the near-infrared spectral regimes commonly used for optical fiber communication. Ultimately, we hope to design practical networks with as many as 5000 nodes which can support multigigabit-per-second channel data rates and have reconfiguration times as short as a few nanoseconds.

4. Device Design

In the design area, we have perfected a theoretical model for calculating nonlinear coefficients and dispersion characteristics of asymmetric quantum wells, and have applied it in a novel design for a frequency conversion device. The design procedure comprises the following steps:

(1) Numerical solution to Schrodinger's equation for arbitrary one-dimensional quantum wells

A computer model which uses a difference-equation technique to obtain numerical solutions to Schrodinger's equation in the effective mass approximation has been developed. The model computes energy levels and wave functions for energy eigenstates of one-dimensional quantum wells . We believe the model to be unique in that it considers bound-continuum as well as bound-bound transitions, and can be applied in cases where the carrier effective mass as well as the potential are functions of position in the well. The model has been applied extensively to asymetric quantum wells in which the composition gradient is linear across the well, and to wells with step asymmetrics. During the course of the work, a new result which extends the Thomas Kuhn sum rule to cases in which the effective mass is a function of position was derived [7]. The effect of an applied electric field on energy levels and refractive indices in asymmetric wells has also been studied [8].

(2) Calculation of second-order nonlinear susceptibility

The expression for the second-order nonlinear susceptibility is obtained using the density matrix formalism in the dipole approximation. The expression contains the sum of a large number of terms, but can be simplified by retaining only the near-resonant terms for which one of the laser frequencies is near an absorption resonance of the quantum well. The matrix elements used in these calculations are determined by numerical integration from the bound and continuum state wave functions obtained in step 1.

(3) Optimization of second-order susceptibility

It is desirable that the magnitude of the nonlinear coefficient be as large as possible. There are two aspects to this. One is to maximize the product of the relevant dipole matrix elements and the other is to achieve the near resonance condition. To this end, QW structures with various

asymmetrical potential profiles including graded-gap and step wells have been studied. These profiles are compatible with present fabrication technology. The QWs must be asymmetrical for the nonlinear coefficient to be non-zero. This is equivalent to the requirement that a bulk nonlinear crystal lack a center of inversion symmetry.

Both bound-to-bound and bound-to-continuum transitions are considered in calculating the nonlinear coefficients. Numerical calculations indicate that the step well gives a considerably larger nonlinear coefficient than the graded well. Example of wave functions and energy levels for the two cases are illustrated in Fig. 7.

Another nonlinear optical effect, nonlinear optical rectification, has also been investigated theoretically. Linearly graded asymmetric MQW structures are predicted to give very large optical rectification coefficients [9].

(4) Intersubband absorption calculation

Intersubband absorption involves dipole transitions between an occupied state (generally, the ground state) and an unoccupied state of the quantum well. To enhance the nonlinear coefficient, it is necessary to achieve the near-resonance condition. This results in strong absorption at the frequency for which energy states are resonant, particularly for bound-to-bound transitions. Strong intersubband absorption at any of three laser frequencies is undesirable as it diminishes the nonlinear optical effect. To reduce this strong absorption between the bound states it is necessary to adjust the well parameters such that the energy levels of the well are off-resonance by an energy substantially greater than the half-width of the absorption line. This reduction in absorption is achieved at the cost of a reduction in the magnitude of the nonlinear optical susceptibility. Thus, there is a tradeoff between achieving a large nonlinear coefficient and reducing the intersubband absorption at the laser wavelength.

(5) Dispersion

For efficient frequency conversion, it is important that the phase matching condition be satisfied. This condition can be written as $\delta = 0$, with δ a phase mismatch parameter given by

$$\delta = n_{1e} f_1 - (n_{2e} f_2 + n_{3e} f_3), \tag{1}$$

where n_{ie} is the effective refractive index of the waveguide mode at the frequency f_i, $i = 1,2,3$. This condition is difficult to satisfy due to dispersion effects attributable to the bulk material properties, the effect of the QWs, and the effect of a waveguide structure in which the QWs are fabricated. QW dispersion is evaluated using the Kramers-Kronig transformation, which relates the change in the refractive index due to the intersubband transition to the absorption coefficient.

Calculations show that for cases of interest it is generally not possible to acheive phase matching in an MQW structure which is uniform in the direction of propagation. The bulk dispersion term results in a monotonically decreasing refractive index, the effect of which is generally much too large to be overcome by QW and waveguide dispersion. However, we believe that quasi-phase-

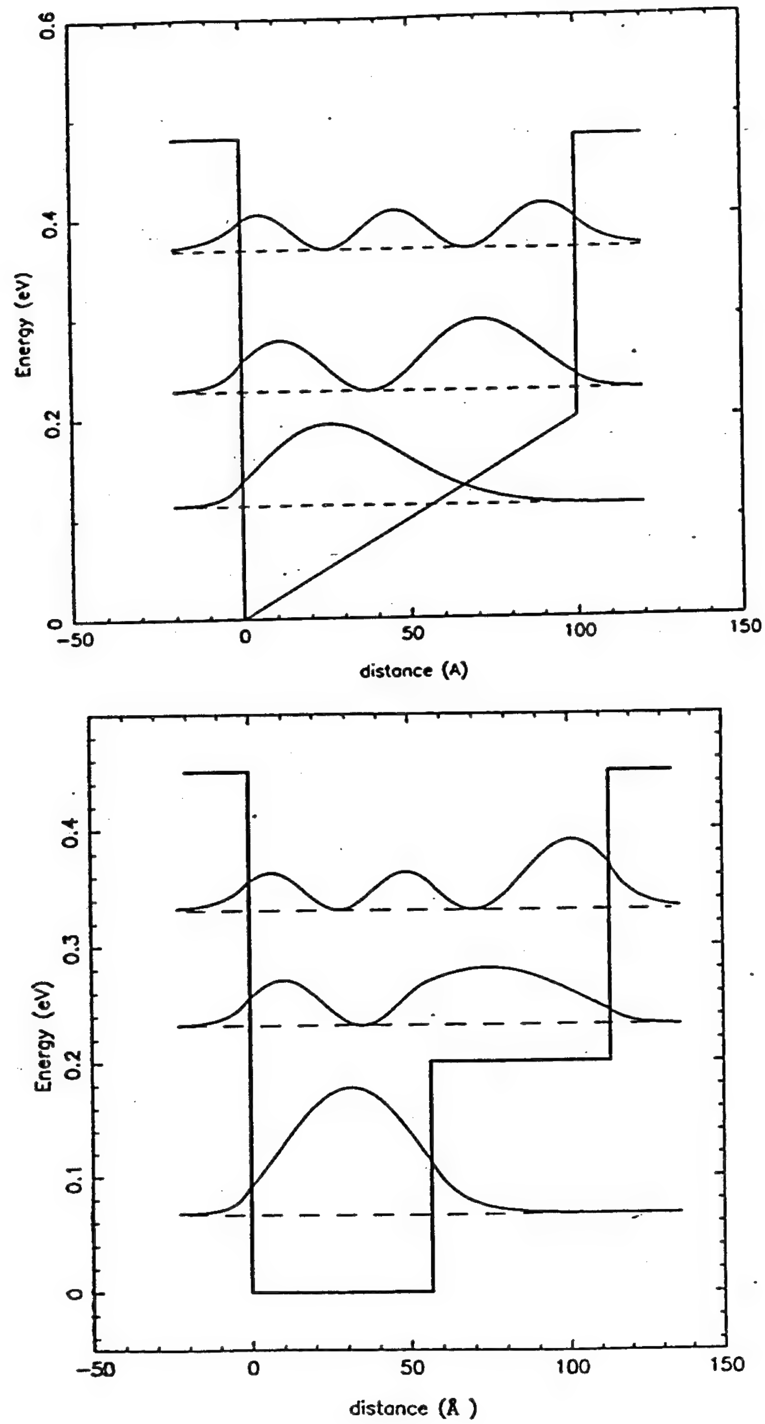

Fig. 7. Asymmetric quantum well designs with corresponding bound-state wave functions and energy levels.

matching (QPM) in which the nonlinear coefficient is a periodic function of position along the propagation direction can be achieved in these materials. In designing a QPM device, a characteristic beat length L_b based upon the combined effects of bulk, QW, and waveguide dispersion is determined from the expression $L_b = c/\delta$, with c the free-space speed of light and δ the phase mismatch parameter from eq. 1. This beat length is incorporated into the design as the spatial period for the nonlinear coefficient variation.

A new approach to QPM in a nonlinear frequency converter based upon Zn diffusion in AlGaAs MQW material is proposed. The diffusion is known to cause a homogenization of the heterostructure layers, thus quenching the nonlinear interaction. By diffusing the Zn through a spatially periodic mask, phase matching can be achieved over a long interaction distance without adversely affecting optical propagation in the waveguide. A device based upon this concept is illustrated schematically in Fig. 8.

(6) Design of nonlinear MQW frequency converter

A model which calculates energy levels, wave functions, dipole matrix elements, second order nonlinear susceptibility, absorption spectra, and dispersion charactristics in QWs has been developed. This model has been applied to the design of nonlinear frequency conversion devices in asymmetric QW structures. To optimize the performance, the effect on conversion efficiency of well height, well width, and the degree of asymmetry has been studied for wells with graded and step asymmetries in the potential.

Numerical results have been obtained for the specific case that photon energies are $E_a = 0.9545$ eV ($\lambda = 1.3$ µm), $E_b = 0.8005$ ($\lambda = 1.55$ µm), and $E_c = 0.154$ eV ($\lambda = 8.05$ µm). The material system is AlGaAs, with $Al_{0.4}Ga_{0.6}As$ in the barrier region, for a maximum well depth for electrons of 0.38 eV. The results indicate that the step asymmetry is preferable to the graded asymmetry. Optimized well parmeters are: well width = 94 Angstroms, step height = 0.15 eV ($Al_{0.2}Ga_{0.8}As$ in the step region), step width 47 Angstroms. This well design is shown in Fig. 9. The quantum well energy levels for the two bound states for these parmeters are $E_1 = 0.098$ eV, $E_2 = 0.242$ eV. The calculated nonlinear coefficient for $10^{18}/cm^3$ electrons in the well, and a power density of 10^6 W/cm^3 at the laser energy E_a is calculated to be $\chi_2 = 7.4 \times 10^{-9}$ m/V. This gives a conversion length with quasi-phase-matching of 112 µm for the nonlinear interaction in which laser light at input wavelengths of 1.3 µm 1.55 µm combine to produce an output at 8.05 µm. A waveguide nonlinear device based upon this MQW design is shown in Fig. 10.

The device structure of Fig. 9 has only one bound state transition. The nonlinear sucsceptibility is large because the bound-state transitions is near one of the photon energies, in this case E_c. The value of χ_2 is enhanced because E_c is near a resonance of the quantum mechanical system. A way to achieve even larger nonlinear coefficients is to use an asymmetric QW structure with three bound states, for which two near-resonance conditions are simultaneously satisfied. Such a structure is illustrated in Fig. 11, with bound-state energies $E_1 = 0.202$ eV, $E_2 = 0.799$ eV, and $E_3 = 0.956$ eV.

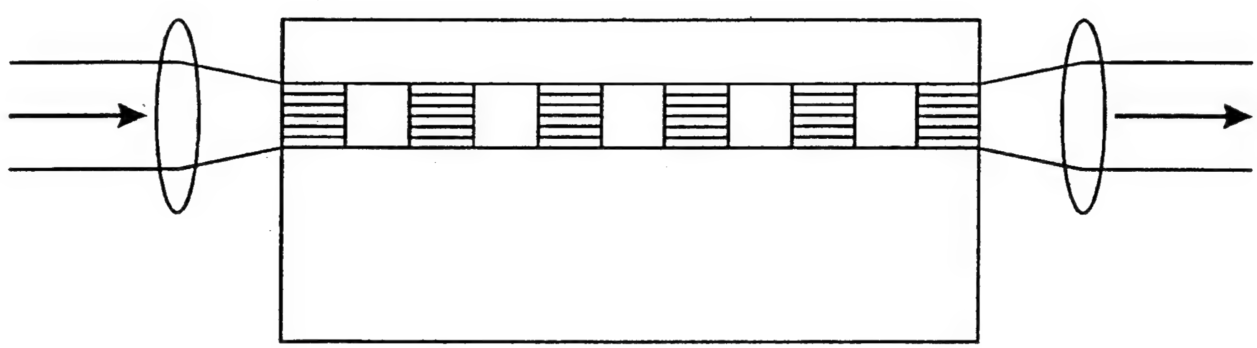

Fig. 8. Concept of quasi-phase-matching in an MQW device with a spatially periodic nonlinearity.

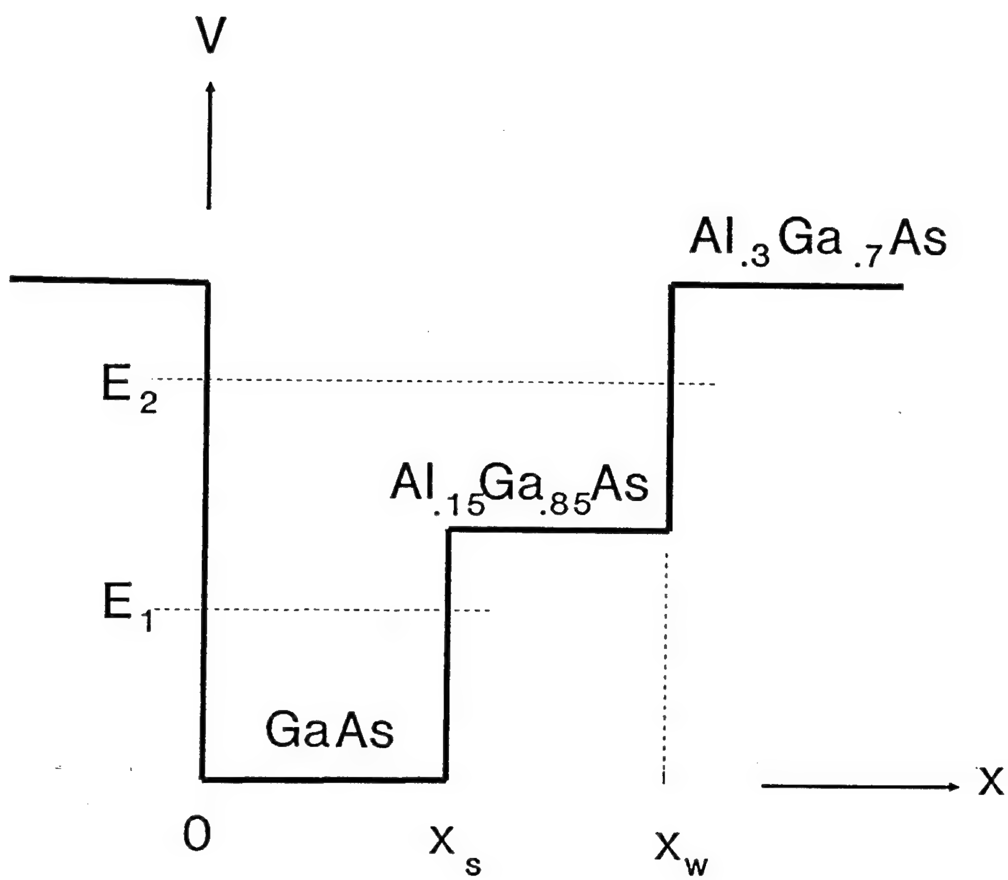

Fig. 9. Design of quantum well for difference frequency mixing at pump wavelengths near 1.3 μm and 1.55 μm.

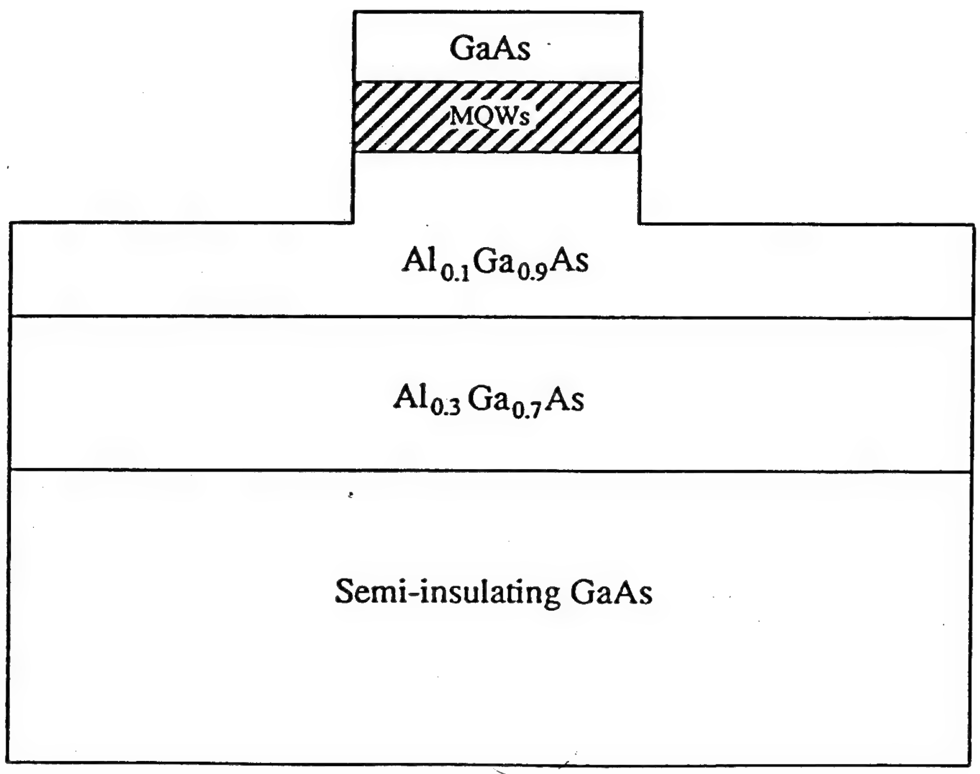

Fig. 10. Proposed structure for nonlinear frequency mixing device in an optical waveguide.

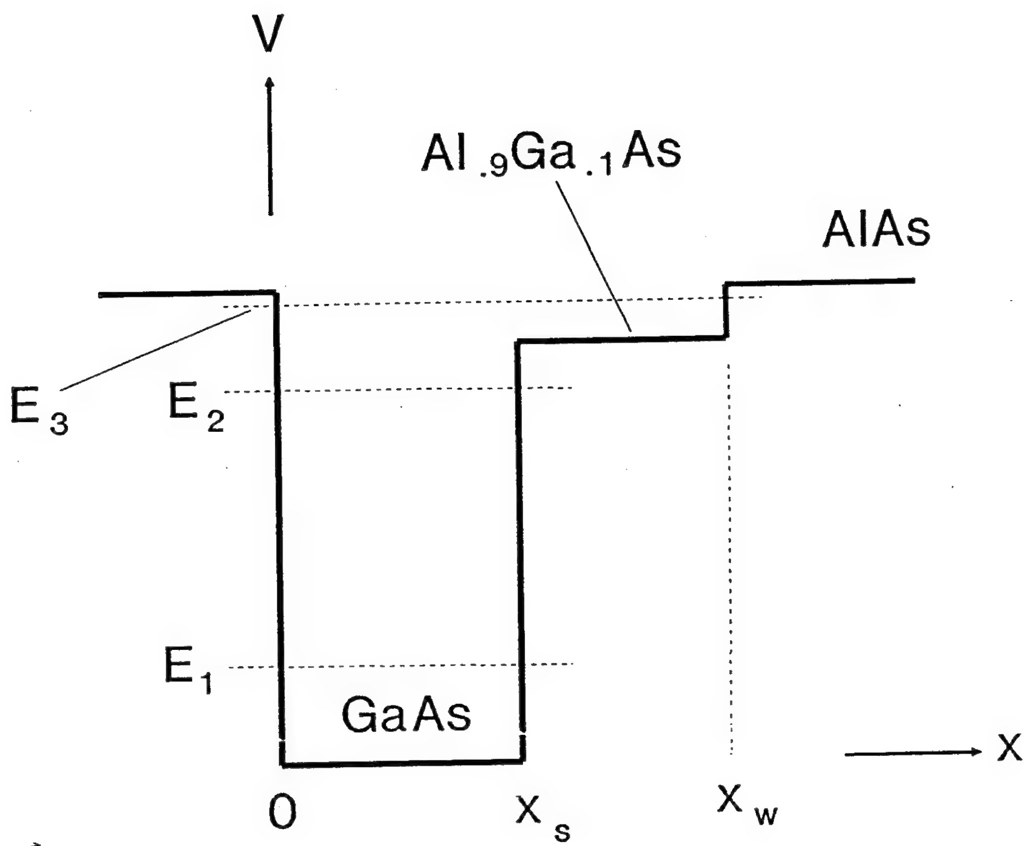

Fig. 11. Quantum well design for enhanced nonlinear susceptibility using a double resonance.

A detailed summary of the nonlinear device design methodology and results is contained in the Ph. D. Dissertation of D. P. Dave [10].

5. Network Application

In many distributed computing systems, latency time as determined by the network bandwidth is a key factor in determining system performance. With the continued rapid growth in the speed and number of individual processors in state-of-the-art systems, this communication bottleneck will become even more important in the years ahead. During the next decade, LANs and WANs with thousands of processors capable of gigabit input/output rates will be developed. Fiber optic networks which effectively utilize the bandwidth of the medium will be needed for effective utilization of the enormous computing power offered by these system. Public-access networks will also grow very rapidly during the next decade, as video-bandwidth fiber optic subscriber loops begin to replace our current telephone system.

It seems likely that wavelength division multiplexing (WDM) will play a major part in the solution to the communications bottleneck, but only after formidable technical problems are overcome. WDM has for several years been one of the most vigorously pursued research topics in the optical communications field. Parallel transmission of channels using multiple wavelength carriers is well established as a cost-effective way to increase the capacity of existing or contemplated fiber installations [1]. However, commercialization of WDM is still at an early stage relative to its potential, and inexpensive components with the performance needed for future data highways are yet to be realized.

Spectral domain processing using nonlinear frequency conversion can play a role in WDM systems of the future, as it provides a way to rapidly switch the carrier frequency of a data stream. We have developed a new network concept which makes use of a nonlinear frequency conversion device to obtain rapid switching between channels in a WDM system. The network is structured as an N-dimensional hypercube connected with single mode optical fibers. Each node has N input and N output fiber lines. Transmission of data packets between nodes in a particular dimension of the hypercube is accomplished using tunable lasers. Each wavelength corresponds to a particular node in that dimension of the hypercube. The laser transmitter is adjusted to the frequency assigned to the desired cross node, at which a fixed frequency selective coupler removes the carrier. Header bits from the packet are read to determine the destination in the new hypercube dimension. Two tunable near-infrared lasers are combined in a nonlinear device, and the resultant mid-infrared output is mixed with the carrier for the data packet to switch to the carrier frequency corresponding to the destination node in the new dimension. This process continues until the data reaches its destination.

An example of a two-dimensional network of this type with N = 2 is illustrated in Fig. 12. A data packet is injected into the network at a wavelength near 1.55 μm from the source node; say, node T-41. The frequency of the source node tunable laser is adjusted to correspond to the frequency assigned to the destination node, say node T-21. The carrier is removed from the fiber bus by a frequency-selective coupler at node T-21. Header bits read at that node indicate that the

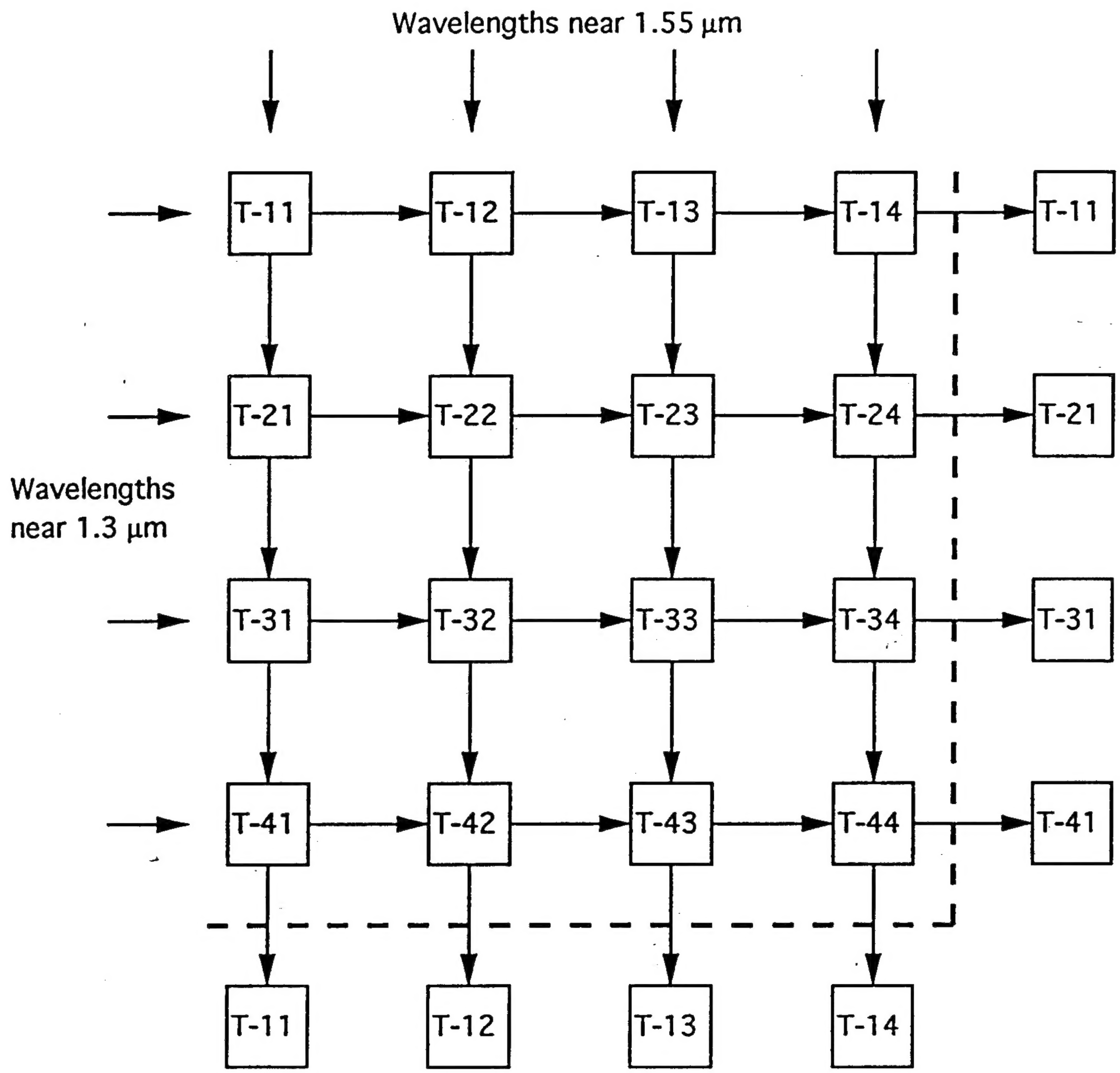

Fig. 12. Two-dimensional network configuration.

final destination is node T-23. CW light from tunable lasers near 1.3 μm and 1.55 μm are mixed in the nonliinear device to produce a difference-frequency output near 8.05 μm. This cw light is combined with the data packet carrier near 1.55 μm to produce a sum frequency corresponding to the frequency near 1.3 μm assigned to the destination node T-23. A frequency-selective coupler at that terminal removes the packet from the bus. The node terminal design is illustrated in Fig. 13.

In this network, the data does not undergo any optical-to-electrical or electrical-to-optical conversion between source an destination. The use of a multi-dimensional architecture reduces the latency time due to propagation delay between nodes by a factor of $Nm^{-(1-1/N)}$ as compared with a one-dimensional linear bus, with m the number of nodes. For example, for a 10x10x10 hypercube with m = 1000 and N = 3, the latency time is reduced to 3% of that for a 1000-terminal linear bus.

We have developed another new network concept which makes use of the frequency conversion device to obtain rapid switching between channels in a wavelength-division-multiplexed system. The system is intended to make efficient use of the 20-50 GHz of bandwidth available in a single fiber in a particular wavelength regime (e. g., the 1.55 μm regime). The destination of a data packet is determined by the carrier frequency injected into the network at the source teminal. The nonlinear device makes it possible to tune to any frequency in the entire wavelength regime in a few nanoseconds. This rapid tunabliity, together with the fact that no processing of the packets is needed at the nodes, provides for low latency time in the network. Further latency reduction as well as improvement in the optical power budget are achieved by multidimensional connectivity.

6. Conclusions

A computer model for the design of nonlinear devices for frequency mixing in multiquantum well (MQW) materials has been developed. The model has been used to calculate nonlinear coefficients for mixing of pump lasers at wavelengths near 1.3 μm and 1.55 μm to produce an output near 8.05 μm. A device length for conversion of 112 μm is predicted for a pump power density of 10^6 W/cm^2. A quasi-phase-matching scheme for obtaining high conversion efficiency in a dispersive semiconductor material is proposed.

An N-dimensional hypercube network configuration making use of the frequency conversion devices has been proposed. The scheme allows for all-optical transmission of data from source node to destination node.

It appears that spectral domain processing based upon multi-quantum-well materials has great potential for use in multi-gigabit-per-second fiber optic communication networks of the future.

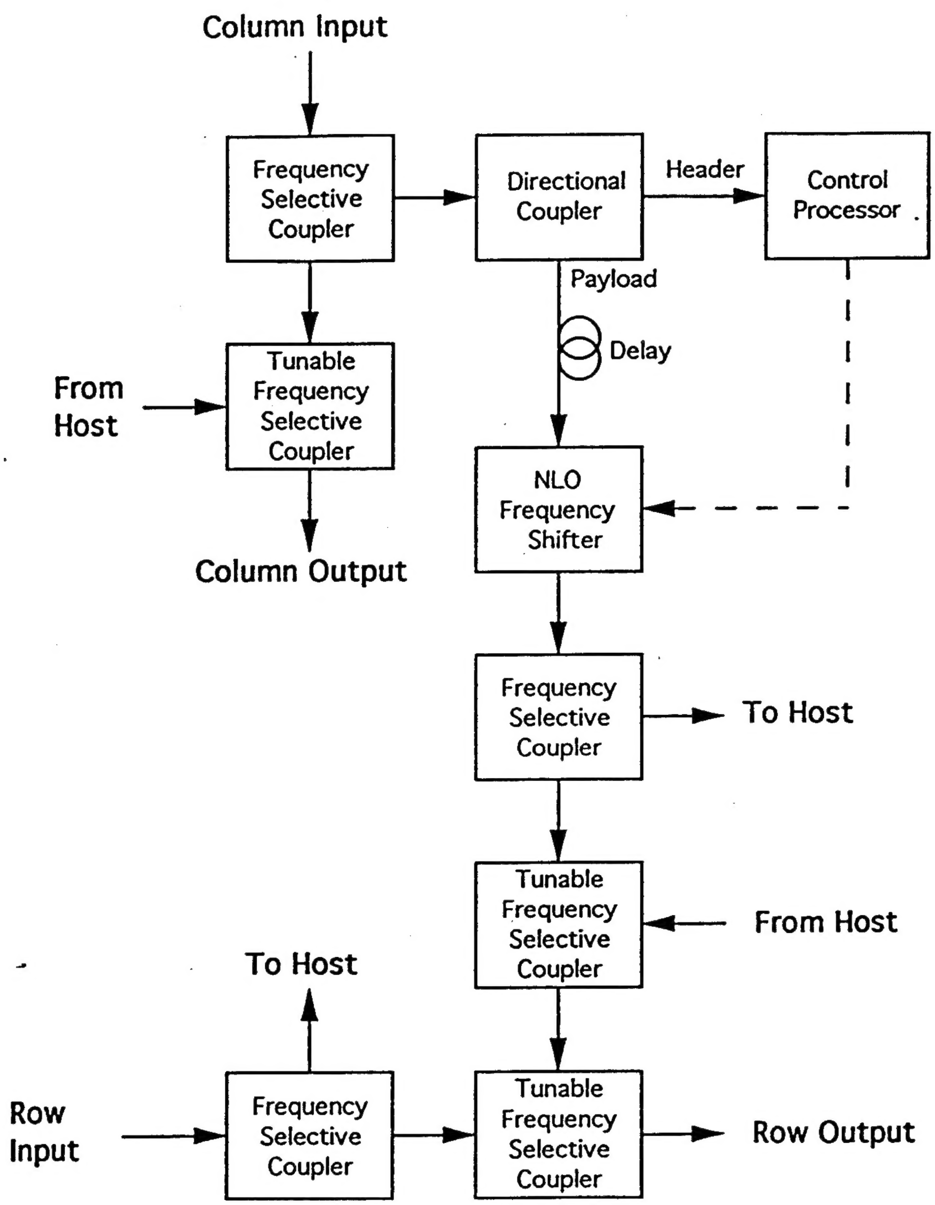

Fig. 13. Design of terminal for two-dimensional network using frequency mixing.

7. References

1. M. K. Gurnick and T. A. DeTemple, "Synthetic nonlinear semiconductors," IEEE J.Quant. Electron., vol. 19, pp. 791-794, May 1983.

2. E. Rosencher, P. Bois, J. Nagle, and S. Delaitre, "Second harmonic generation by intersub-band transitions in compositionally asymmetrical MQWs," Electron. Lett., vol. 25, pp. 1063-1065, Aug. 3, 1989.

3. M. M. Fejer, S. J. B. Yoo, R. L. Byer, A. Harwit, and J. S. Harris, "Observation of extremely large quadratic susceptibility at 9.6-10.8 æm in electric-field-biased AlGaAs quantum wells," Phys. Rev. Lett., vol. 62, pp. 1041-1044, Feb. 1989.

4. D. A. Holm and H. F. Taylor, "Infrared phase modulators with multiple quantum wells," IEEE J. Quant. Electron., vol. 25, pp. 2266-2271, Nov. 1989.

5. J. D. Wiley, "Mobility of holes in III-V compounds," in Semiconductors and Semimetals, vol. 10 (ed. by Willardson and Beer, p. 101).

6. C. M. Wolfe, N. Holonyak, and G. E. Stillman, Physical properties of semiconductors, (Prentice Hall, Englewood Cliffs, N. J., 1989), p. 340.

7. D. P. Dave and H. F. Taylor, "Thomas-Kuhn sum rule for quantum mechanical systems with a spatially varying effective mass," Phys. Lett. A, vol. 184, pp. 301-304, 1994.

8. D. P. Dave, "Enhanced refractvie index change in asymmetrical quantum wells with an applied electric field," J. Appl. Phys., vol. 74, pp. 6872-6875, Dec. 1, 1993.

9. D. P. Dave, "Optimisation of nonlinear optical rectification in linearly graded AlGaAs quantum wells," Electron. Lett., vol. 28, pp. 1603-1605, Aug. 13, 1992.

10. D. P. Dave, "An investigation of nonlinear frequency mixing in semiconductor quantum wells," Ph. D. Dissertation, Texas A&M University, Dec. 1994.